Co-seismic rupture patterns over multiple earthquake cycles near Kodiak Island: a collaborative project with USGS personnel

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Summary

The 1964 Mw 9.2 Alaska megathrust earthquake was the largest recorded earthquake in North America and second largest instrumentally recorded worldwide earthquake. The megathrust earthquake caused considerable damage to southern Alaska from Kodiak to Cordova, and tsunami-related damage and loss of life was realized around the Pacific. The quake, centered beneath Prince William Sound (Figure 1), produced more than $100 million in damage and more than 100 deaths, destroyed 30 city blocks in Anchorage (120 km from the epicenter), and approximately $10 million in tsunami-related damage and 13 deaths in California alone (e.g., Sokolowski, 1991). This report summarizes legacy and new seismic/gravity data for the Kodiak segment of the Alaska subduction zone. This subduction zone segment, one of three asperities that ruptured during the 1964 earthquake, produced considerable damage to the Kodiak coastal communities from tsunami run up and ground shaking. The objective of this study was to identify and characterize active faults that may be responsible for tsunami generation both during the 1964 earthquake and past events. During a

poor weather window, we surveyed the Pillar Mountain landslide near Kodiak City and summarize the findings in this report.

Our results point to a semi-permanent southwestern segment boundary related to the Kodiak asperity, slip rates upwards of 5 mm/year for a left-stepping set of Kodiak shelf faults and tremendous variation in uplift rates and structures along the Albatross Bank faults. Uplift along the Albatross Bank faults (maximum 1-2 mm/yr), as measured by sea floor scarp heights, appears to be less than that measured along the Kodiak Shelf fault system. Our seismic imaging campaign related to the Pillar Mountain landslide does not support a more extensive slide beyond previous assessments.

Project overview

Prior to this project and past USGS-funded Boise State cruises, identification, mapping, and characterizing the crustal architecture and faults within PWS and Gulf of Alaska have been limited to geologic mapping on islands (e.g., Plafker, 1969; 1972) and regional geophysical surveys. These surveys include potential field surveys (e.g., Barnes, 1991; Barnes and Morin, 1990; Griscom and Sauer, 1990; Saltus et al., 2007) crustal seismic reflection and refraction surveys related to the TACT/EDGE/ALEUT experiments (e.g., Moore et al., 1991; Brocher et al., 1994; Fuis et al., 2008; Shillington et al., 2011), and earlier analog datasets (e.g., von Huene et al., 1979; Fisher and von Huene, 1980; Carlson et al., 1978). High quality multibeam data exist throughout PWS, but not in the open waters of the western Gulf of Alaska near Kodiak Island. Sparker seismic data that highlight Holocene slip history for the PWS region (Liberty et al., 2013; Finn et. al., 2015; Haeussler et al., 2015) do not exist for the presumed active faults related to the Kodiak asperity.

Although our approach for this funded project was to acquire detailed sparker seismic data across the Kodiak segment, inclement weather limited our survey to a single day offshore Kodiak city. This survey, conducted on the USGS R/V Solstice under Captain Greg Snedsen and USGS collaborator Peter Haeussler, departed and returned to Homer, Alaska with down time in the port city of Kodiak. The seismic data on the only good weather offshore day were acquired at rapid boat speeds (6-7 knots) to characterize a presumed fault scarp related to the Albatross Bank faults, at a sacrifice of data quality. The data were acquired with a 500 Joule sparker (Texas A&M) and a 12-channel solid state streamer (24-channel streamer was lost with equipment mobilization). As a result of this limited boat time and in addition to interpreting this one-day sparker seismic profile, we examine tsunami first arrivals recorded on the Kodiak Islands (Plafker, 1965), new marine gravity data from satellite altimetry (http://topex.ucsd.edu/marine_grav/mar_grav.html) and seismic data acquired by Mineral Management Services in 1978 (Liberty, 2013). Compilation of these legacy airgun seismic data (Liberty for NEHRP #G12AP20078) has resulted in the assessment of nearly 100 Gulf of Alaska seismic profiles (mostly near and off the shelf break). In addition to these data, we also examine sparker seismic profiles acquired during the 1970's and data from a new sparker seismic survey near Kodiak City. These data were acquired in 2015 during a poor weather window related to this project and complement a chirp seismic campaign summarized by Moore et al. (1980).

Results presented in this report are divided into three sections. First, faults along the Kodiak shelf fault system are characterized from seismic and gravity data, first arrival tsunami information, and from bathymetric maps. Next, we present seismic profiles from the Albatross Bank region. Many of these faults were identified by von Huene et al. (1976); Fisher and vob Huene (1980) and subsequent reports. Two new sparker profiles from this study are added to the characterization of the Albatross Bank faults. Lastly, we summarize findings from the Pillar Mountain landslide region near Kodiak city based on new sparker seismic data.

Gravity data

Gravity images were created by filtering and upward continuing raw data. Figure 1 shows a free air gravity map with wavelengths greater than 240 km removed. We then used a hillshading approach to highlight northeast-trending lineations. The results highlights faults that were active in 1964 and from past megathrust earthquakes. These faults include the Patton Bay and Cape Cleare faults (Liberty et al.., 2013) and the Kodiak Shelf faults (this report).

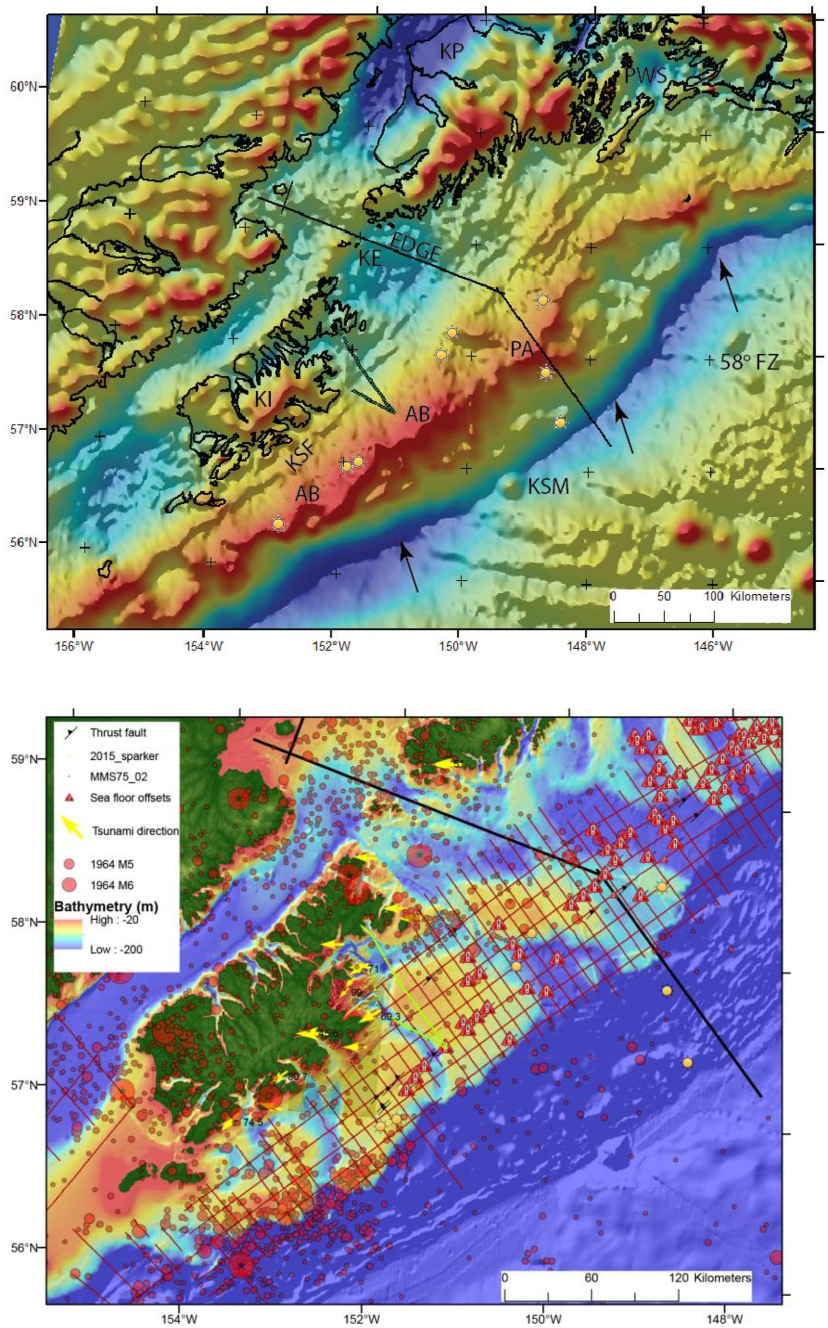


Figure 1. (top) Free air gravity map for the Gulf of Alaska region filtered to remove signals with wavelengths greater than 240 km and shaded from the northwest to highlight gravity lineaments related to subduction zone splay faults. Green dots represent 2015 sparker seismic profile transect to a strand of the Albatross fault system, black arrows represent trench location with Pacific plate motion direction and yellow circles represent exploration borehole locations. AB=Albatross Bank, KE=Kennedy Entrance, KI= Kodiak Island, KP=Kenai Peninsula, KSF=Kodiak Shelf faults, KSM=Kodiak sea mount, PA=Portlock Anticline, PWS=Prince William Sound, EDGE=EDGE seismic profile (Moore et al., 1991). (bottom) MMS seismic profile locations with earthquake epicenters and mapped faults from the MMS database

Kodiak Shelf fault system

The Kodiak Shelf fault system includes the Kodiak Island and the Narrow Cape faults that extend across the Kodiak islands and Gulf of Alaska (Figure 1). Von Huene et al. (1980) identified at least three ~N45°E faults within this fault zone that have produced seafloor scarps and these scarps appear on the filtered gravity map. Carver et al. (2008) inferred that the tectonic scarps are post last glacial maxima (LGM or 10-15 ka), providing constraints on Holocene slip. We compiled a dense network of unpublished sea floor bathymetry and sparker/airgun seismic datasets to identify and characterize tectonic sea floor scarps related to the Kodiak Shelf fault system (Figure 2). The seismic data come from three sources. The 1978 MMS airgun profiles were nominally acquired every 10 km across the length of the shelf system (Liberty et al., 2013) while a 1977 sparker survey was acquired every 4-6 km (Figure 2). Two 2015 sparker seismic profiles were acquired across the Kodiak Shelf fault system (Figure 1). Additionally, we used sea floor bathymetric measurements to back-propagate tsunami travel times compiled by Plafker (1969) from the mainshock of the 1964 earthquake to estimate first-arrival tsunami sources from several inundated sites along Kodiak Island. We used a finite difference approach to with a 5 km cell size and tsunami propagating speeds relative to the average water depth within each cell.

The first arrival tsunami wave front models converge to a narrow region offshore Sitkalidak Island near the Kiluda Trough (Figure 2), where active-source seismic and bathymetric data show a scarp (upwards of 50 m) related to the Kodiak Shelf fault zone (here termed fault A). The seismic data (Figure 3) suggest growth on this fault that is consistent with a long-lived fault. However, significant variation in sea floor uplift on seismic profiles spaced 10 km (25 m and 50 m scarps on sparker 252 and MMS 484 respectively) and on sparse bathymetric data suggest along-strike variations in coseismic uplift. Near this location, earthquake, tsunami and geodetic data suggest approximately 10 m of lateral slip confined to a relatively narrow region on the megathrust during the 1964 earthquake (Ichonese et al., 2007). Given the height of the sea floor scarp associated with fault A of the Kodiak Shelf fault zone, we infer repeated Holocene coseismic uplift consistent with local tsunamis impacting the Kodiak Islands over multiple earthquake cycles. With post-LGM uplifts of 25-50 m, we assign a Holocene slip rate of 1.5-5 mm/year for this fault. Faults that laterally slipped 20 m along the megathrust near PWS show vertical uplifts of 8-10 m (Liberty et al., 2014). Here, we suggest 4-5 m of vertical uplift from the documented 10 m slip on this fault system (Ichonese et al., 2007). This uplift produced the local tsunami documented by Plafker (1969) on the Kodiak Islands and this uplift rate is consistent with 10-12 post-glacial coseismic earthquakes with similar uplift patterns. Thus, if this pattern persists through time, we suggest this fault results in tsunamigenic motion approximately every 1,000 years. However, since only a small portion of this fault presumably moved in a tsunamigenic manner in 1964 and since sea floor scarps are continuous along this fault, slip along this fault likely occurs at more frequent intervals where different portions of the fault may experience focused uplift. This fault motion model may explain recurrence intervals of 500-600 years documented by Carver and Plafker (2002). Sea floor scarps related to fault A diminish to the west of the Kiliuda trough, but continue seaward along a subparallel lineation that we term fault B. To the northeast, the sea floor expression of fault A terminates near the Chiniak Trough (Figure 2). However, no detailed bathymetric surveys within Chiniak Trough and farther east are available.

To explore the northeast extension of the Kodiak Shelf faults, we show two sparker seismic profiles acquired in 2015 and integrate the gravity data shown in Figure 1. The filtered gravity map shows a prominent scarp associated with fault A that terminates near the Chiniak Trough. Where the gravity lineament is prominent to the west of Chiniak Trough, the bathymetric data (https://data.noaa.gov/dataset/kodiak-alaska-8-arc-second-dem) suggest a 30 m fault enhanced scarp. The Chiniak Trough sparker profile (Figure 4) shows a 10 m scarp with growth strata that is along strike of fault A and the Albatross Bank sparker profile shows a 4 m scarp with limited growth of Holocene and older strata. The diminished sea floor expression to the northeast suggests fault A terminates near the Chiniak Trough. Gravity data suggest an additional landward-stepping fault extends to the northeast. Our new sparker and legacy MMS seismic data do not show clear evidence for this gravity lineation, thus we provide no detailed analysis of this presumed fault.

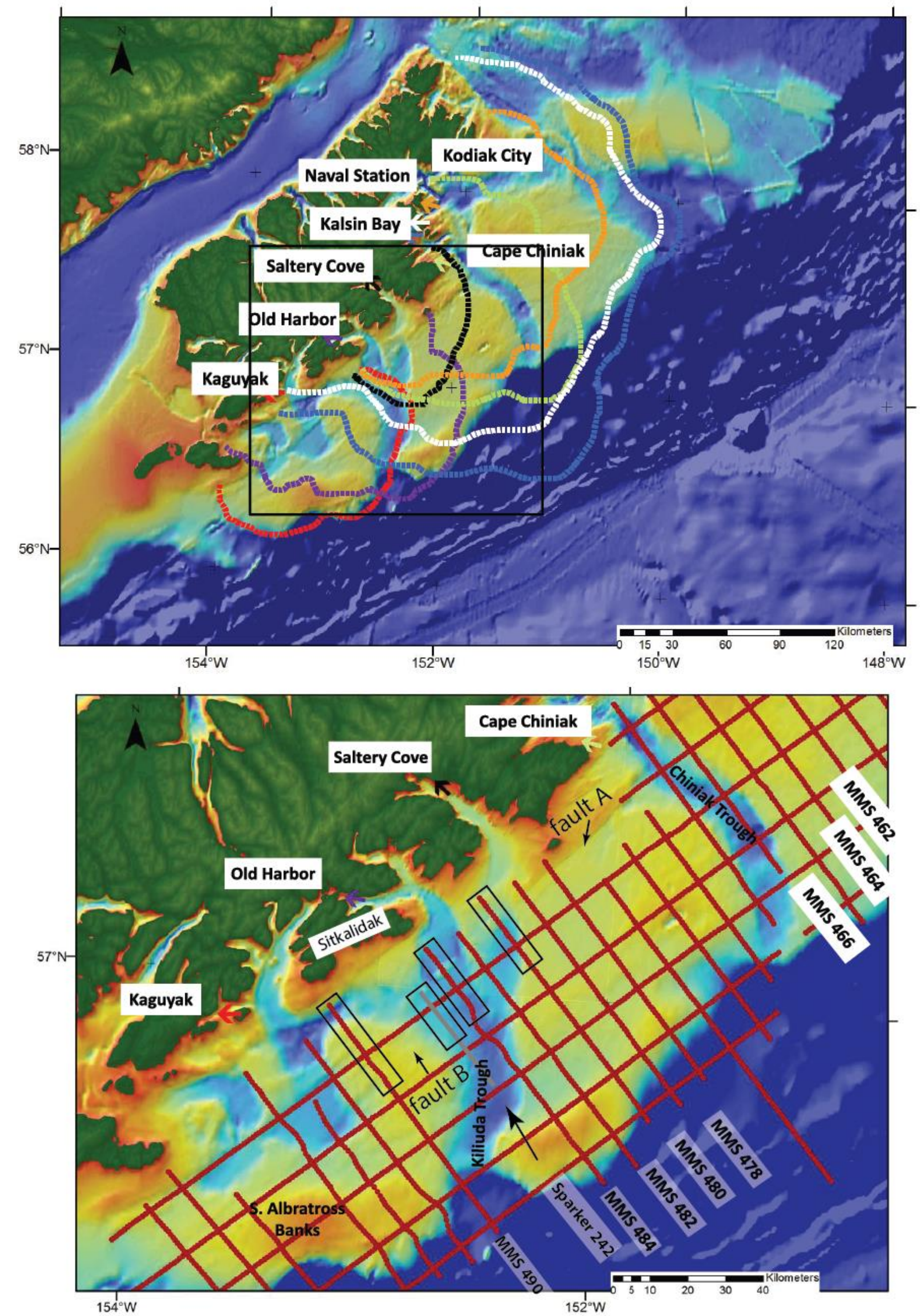


Figure 2. (top) Bathymetric map with tsunami model results showing back-propagated each tsunami wavefield travel times from Plafker (1969). (bottom) Kodiak Shelf fault region with MMS seismic profile locations and Line 282 legacy sparker profile.

Farther southwest along the Kodiak Islands, we identify fault B as a seaward stepping active fault related to the Kodiak Shelf fault system (Figure 2). This fault offsets the sea floor west of Kiluida trough (Figure 3), but little sea floor uplift is apparent to the northeast. MMS profile 490 and sparker profile 242 both show sea floor offsets of about 5 m, or 5-10 times less than fault A. Thus, we assign a slip rate of 0.15-0.5 mm/year for fault B. However, bathymetric data in this region are sparse and precise sea floor uplift estimates are lacking.

From seismic data alone, the length of the Kodiak shelf faults are difficult to assess. Sea floor bathymetry and seismic data suggest the Kodiak shelf faults are a series of left-stepping thrust faults that are responding to oblique shortening along the megathrust. These faults extend the length of the Kodiak Islands, but limited seismic and bathymetric measurements provide a limited hazard assessment. Gravity data suggest these faults extend along strike for more than a few hundred km. The filtered gravity map shown in Figure 1 suggests that Fault B may extend a considerable distance to the southwest beyond the Kodiak Islands to at least Chirikof Island (southwest limit of Figure 2a map) and across the presumed southwestern segment boundary (and limit of 1964 uplift) related to the Kodiak asperity. This assessment is consistent with the Briggs et al. (2014) observations that the 1788 earthquake extended crossed multiple segments (including the Kodiak asperity) from the southwest. Thus, the southwest limit of the Kodiak asperity is likely a semi-permanent rupture boundary that may slip with earthquakes that initiate from the northeast (such as 1964), from the southwest (such as 1788), and as an independent segment rupture (e.g., Shennan et al., 2014). More detailed bathymetric mapping and high resolution seismic data could help refine the hazard assessment for the Kodiak Shelf fault system.

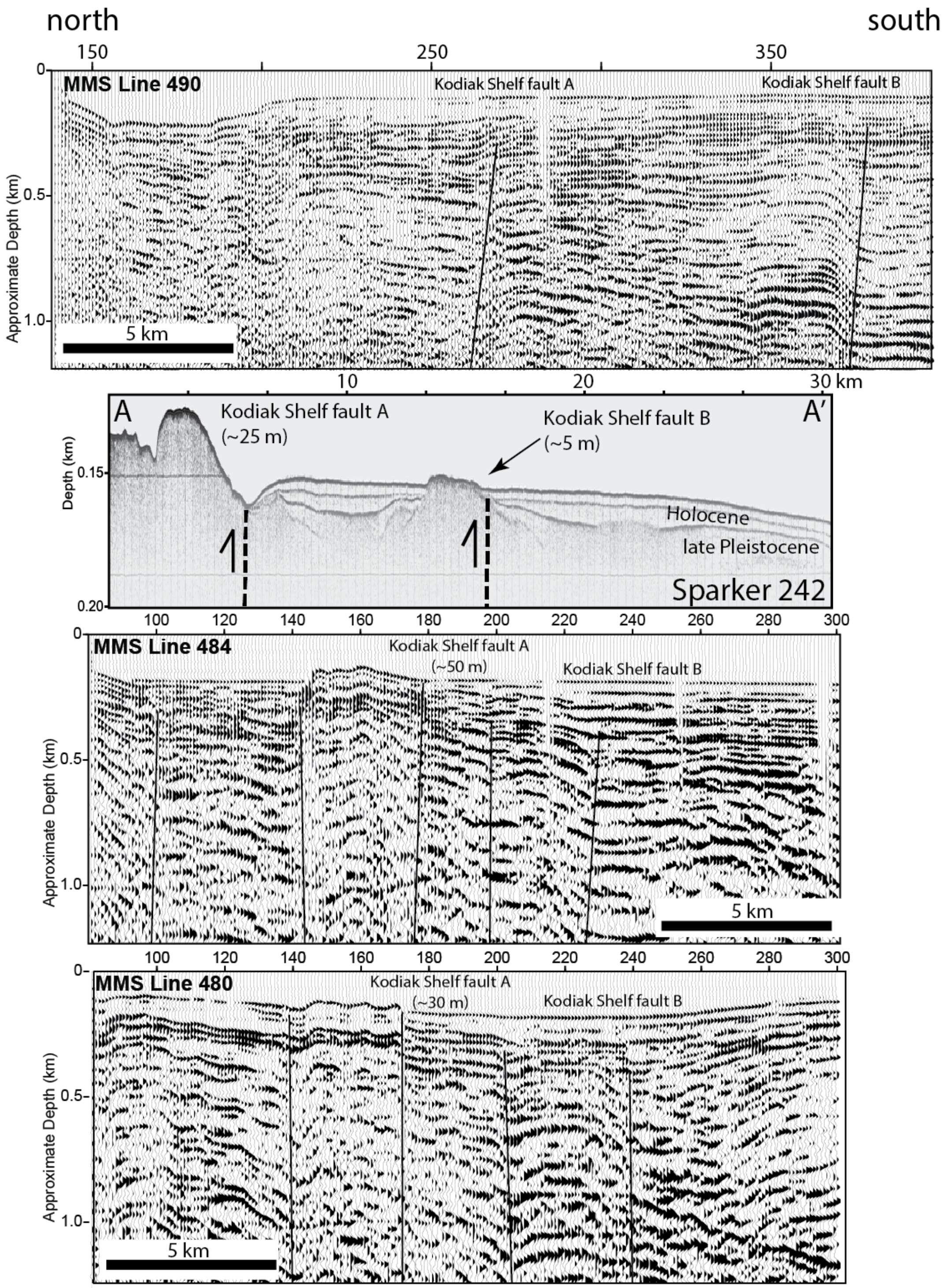


Figure 3. (top) Legacy sparker seismic profile 242 and MMS profiles 480 and 484 and 490 showing faults related to the Kodiak Shelf fault system. Note the variation in uplift along the faults on the parallel profiles (see map on Figure 2). Fault B shows a surface expression on the sparker profile, but not on adjacent MMS airgun profiles. The largest scarp related to fault A is mapped on MMS profile 484, consistent with 1964 tsunami source.

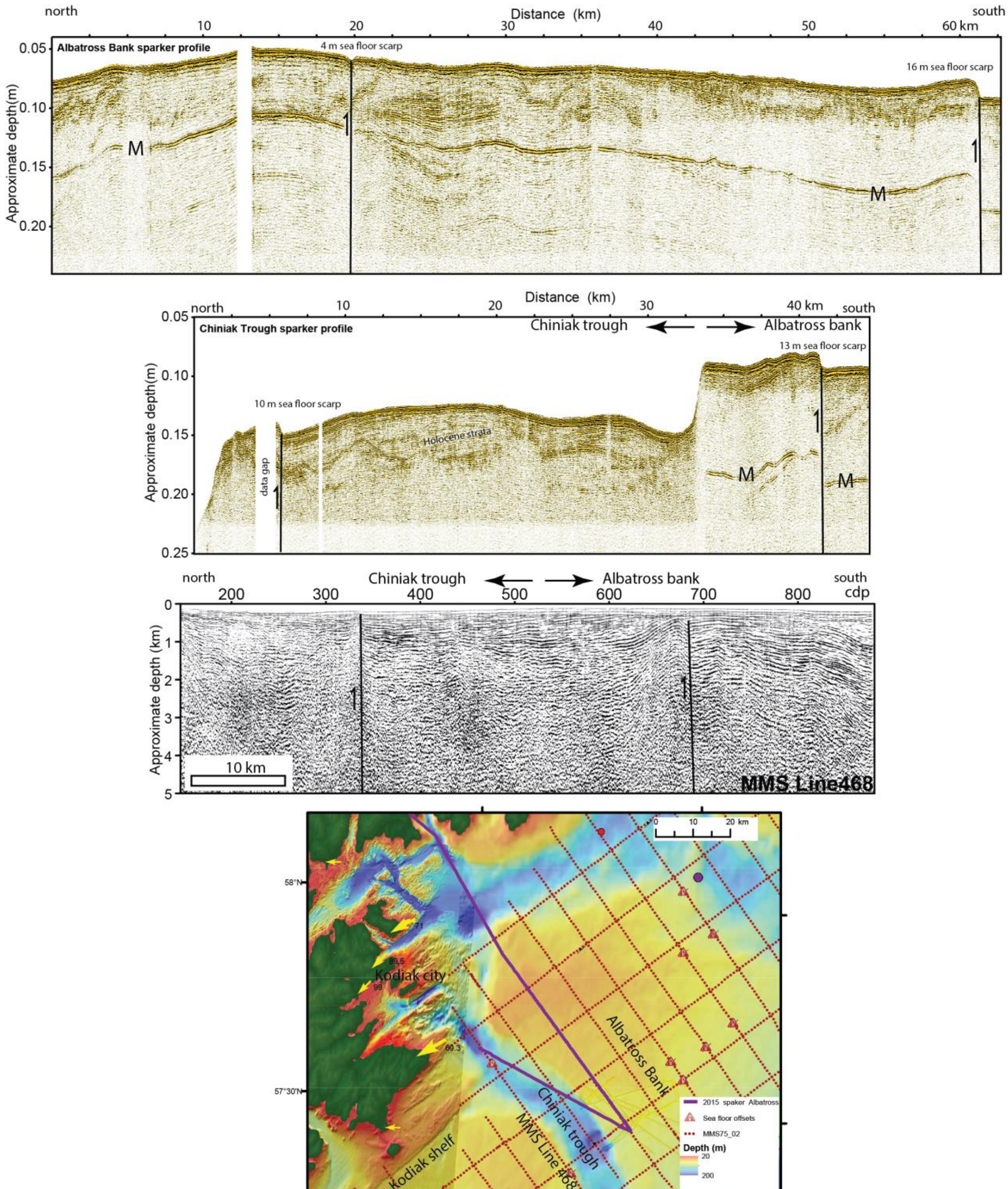


Figure 4. (top) Sparker seismic data from 2015 across the Albatross Bank and Chiniak Trough. Legacy MMS 468 profile shows the deeper character of the identified faults to suggest they have been active for many earthquake cycles. (bottom) Bathymetric map showing seismic profile locations. Note the change in bathymetric resolution to the west of Chiniak Trough.

Albatross Bank structures

Von Huene et al. (1980) defined the Albatross Bank as the shelf region immediately south of Kodiak Islands (Figure 1). They made interpretations from high-frequency single-channel seismic data, documented many small sedimentary basins, and concluded that several northeast-striking en-echelon faults that bound these basins on Albatross Bank merge, along strike, into folds. This study documented both landward- and seaward dipping, high-angle faults. Ichonese et al (2007) documented upwards of 10 m of slip along the Albatross Bank during the 1964 earthquake, but this uplift was centered along a relatively narrow strip of the continental shelf and slope. We add seismic images from the MMS dataset to better document tectonic structures and faults that lie beneath the Albatross Bank (Figure 4). Additionally, we acquired two sparker seismic profiles (out and back across the shelf) across an 18 m scarp related to the Albatross Bank fault system (Figure 5).

Figures 4 shows three MMS seismic profiles that cross strands of the Albatross fault system. From these profiles that are spaced 10 km apart, we highlight a sea floor scarp that is significantly offset and rooted in a fault. The measured 18 m sea floor scarp on MMS 464 with growth on the underlying Miocene and younger strata suggest a thrust fault has been active for thousands of earthquake cycles. However, adjacent profiles show essentially no sea floor scarp and significantly less Quaternary slip. This fault, along with other identified faults on the MMS profiles, suggest complex pattern of coseismic slip related to the Albatross Bank fault system. The narrow slip patch modeled by Ichonese et al. (2007) is consistent with the Albatross Bank faults slipping within a narrow patch for a given earthquake cycle. Although this patch may migrate through time, the large and localized scarp shown on the Chiniak sparker and MMS 464 profiles suggest that uplift related to megathrust faulting along the Albatross Bank may be persistent through multiple earthquake cycles.

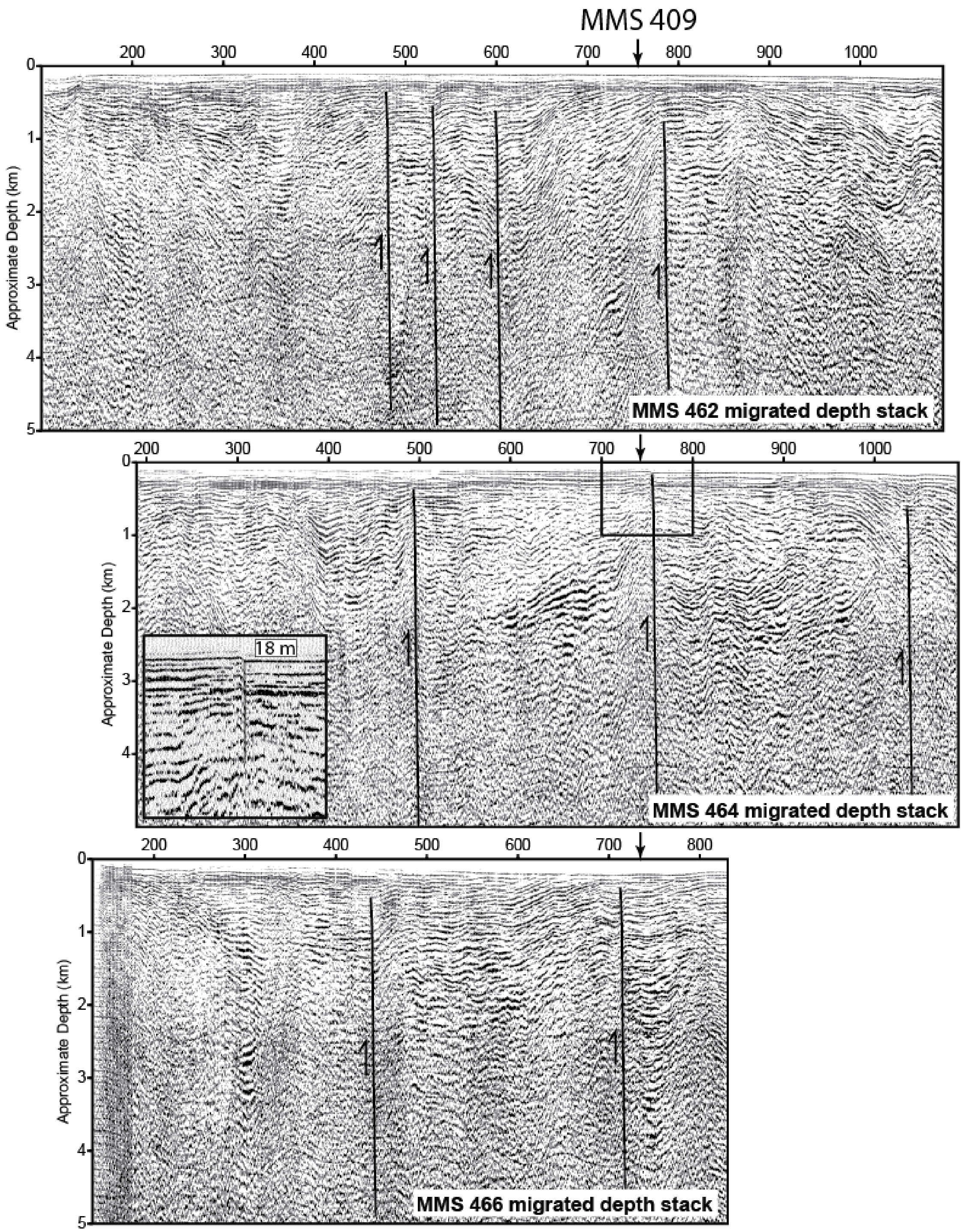
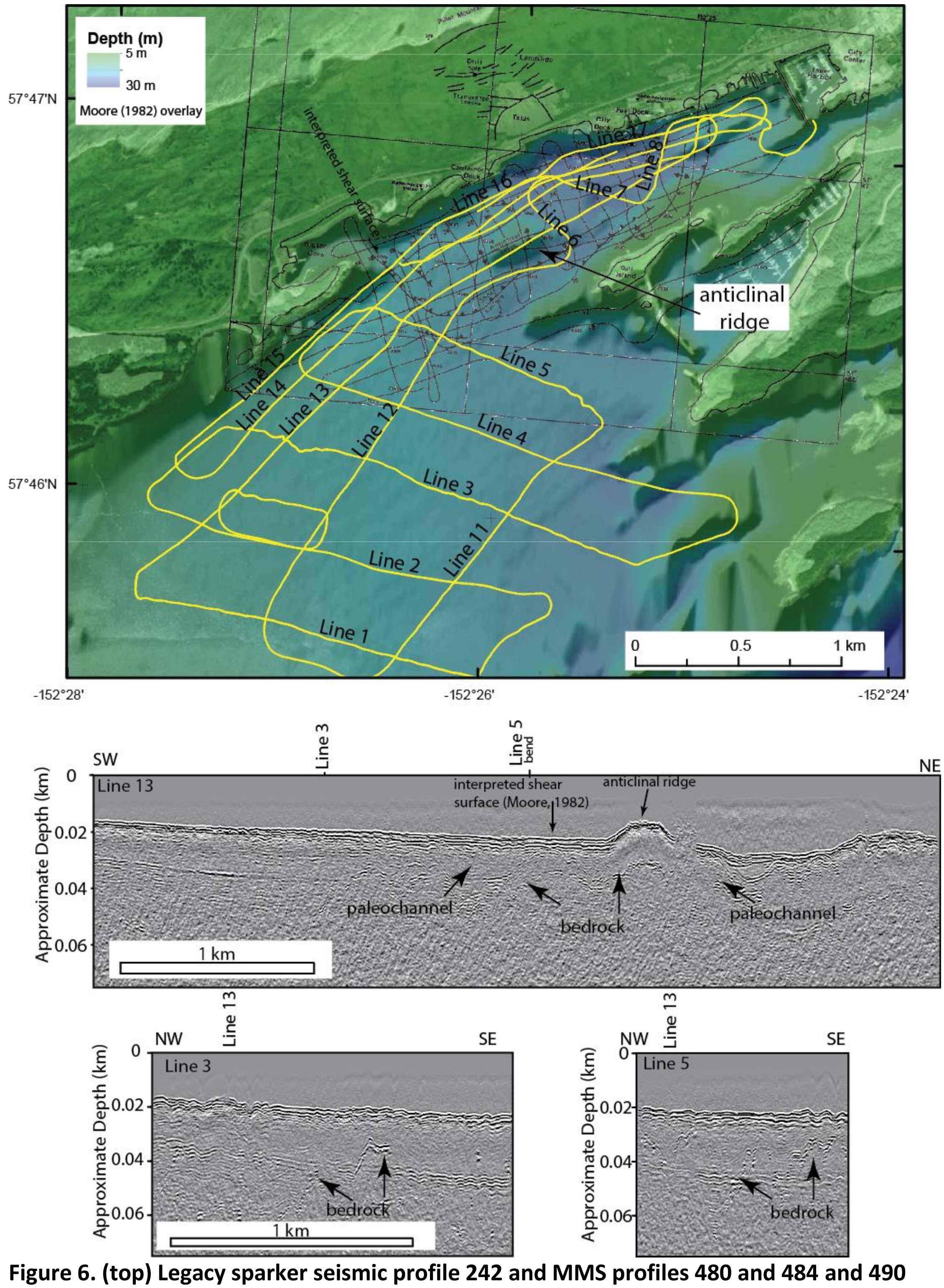


Figure 5. MMS seismic profiles across the Albatross Bank faults. Note the significant change in basin strata and fault character across the mapped fault (e.g., von Huene et. al, 1980). MMS profile 464 shows the greatest sea floor displacement at 18 m. Profiles 462 and 466, both spaced 10 km from MMS 464 show little to no sea floor displacements.

Pillar Mountain landslide

The southeast facing Pillar Mountain landslide lies about two kilometers southwest of the City of Kodiak, Alaska (Figure 6). The 340 meter high slide lies on a 45 degree glacially enhanced slope that has moved as late as 1971 (Moore, 1982). The hillslope contains interbedded Late Cretaceous age Kodiak Formation rocks and is overlain by a talus derived from this rock at the base of the slide. Concerns relating to a large slide raise the possibility of a local tsunami source from a rock avalanche has motivated this seismic survey to identify paleoslide materials beneath Kodiak Harbor. Moore et al. (1982) observed that bay-floor reflectors are nearly planar, and identified locally folded strata crosscut by reflectors. The deformed sediments were tied to a broad (200 m wide) anticlinal ridge surrounded by a shear surface as defined by the crosscutting reflectors (Figure 6). Moore interpreted the deformation as being related to push from the Pillar Mountain landslide (Figure 6).

While the original survey focused on reflectors in the upper 20 m below sea floor, we extended our survey to bedrock depths, approximately 20-40 m below sea floor and to the surrounding region. We find significant variation in bedrock topography with relatively flat lying strata lying above a seismically transparent zone and an undulating bedrock surface. We do not see regions of truncated reflectors that would suggest mobilized materials related to the Pillar Mountain slide. We identify paleochannels that have provided material pathways during lower sea level times. These paleochannels suggest high energy depositional environment that may explain folded and truncated strata. Although we do not refute the findings of the Moore (1982) study, we do not see evidence for pervasive landslide materials in the waters surrounding Kodiak Harbor.



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Summary

Seismic, bathymetric and gravity data were analyzed to assess earthquake hazards along the seaward portions of the Kodiak Islands. We identify and characterize an en-echelon pattern of faults that likely slipped during the 1964 earthquake. Detailed multibeam and modern seismic imaging of these faults will help improve the hazard assessment for these faults.

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